# ADVANCES IN HIGH-POWER TARGETS

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*Abstract*

High-power targets are a major issue for both neutron sources and neutrino factories. This paper reviews the status of international studies. The targetry R&D program required to realize high-power targets is described.

## INTRODUCTION

There exists worldwide interest in the development of new high-power proton machines which are capable of delivering beam powers of 1MW and greater. These machines are foreseen to provide a variety of applications including the transmutation of nuclear wastes, the operation of sub-critical power reactors, the production of nuclear materials such as tritium and other isotopes useful for medical applications. However, the application, which most interests the international physics community, is the prospects for the production of intense secondary beams that will provide the programmatic basis for the discovery of new physics. These secondary beams include neutrons which are particularly useful in understanding solid state phenomena, kaons for the search for rare physics processes, muons for solid state and particle physics studies, and neutrinos for a clearer understanding of recently confirmed oscillations and the possibility of CP violation in the lepton sector. These applications have in common the need to develop solutions for beam targets that can survive intense MW class beams.

## TECHNICAL CHALLENGES

A variety of technical issues accompany the development of target systems capable of exploiting high-power primary beams. Among these issues are:

- Thermal management
    - Target melting
    - Target vaporization
    - Heat removal
- Radiation
    - Radiation protection
    - Radioactivity inventory
    - Remote handling
- Thermal shock
    - Beam induced pressure waves
    - Cavitation
- Material properties
    - Yield strengths
    - Thermal conductivity
    - Thermal expansion
    - Resistance to irradiation damage

An important parameter to consider in target design is the energy deposition density, U (usually expressed as J/g), resulting from the interaction of particles traversing the target medium. Until recently, values of U in excess of 100 J/g where considered aggressive but as we shall see this is routinely exceeded in high-power applications. Through an inspection of the equation:

$$Stress = Y\,\alpha_T\,U / C_V,$$

where Y is the bulk modules, $\alpha_T$ is the coefficient of thermal expansion, and $C_V$ is the thermal heat capacity, one sees that several properties of the target material affect induced strains and therefore stresses in the target. Clearly a target would benefit from low values of the modulus, the coefficient of thermal expansion, and high values of the heat capacity. Additional material property considerations are a high tensile strength (particularly important for pulsed beams) and thermal conductivity.

Finally, the susceptibility of material properties to be modified as a result of exposure to radiation is an important consideration.

## EXAMPLE SOLUTIONS

We consider a variety of target solutions to illustrate the diversity of the efforts toward solving the technical challenges of developing high-power targets. To date both solid and liquid targets have been pursued.

### *Static Solid Targets*

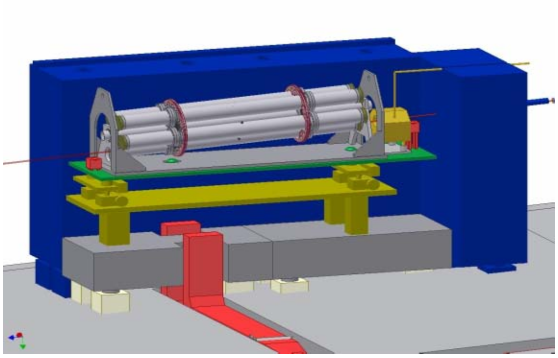

Figure 1a: The CERN CNGS Target=segmented carbon 750 J/g pulsed air-cooled.

Examples of static solid targets include:

- The CERN CNGS neutrino source (Figure 1a)
- The FNAL NUMI neutrino source (Figure 1b)
- The T2K neutrino source (Figure 1c)
- The Los Alamos SNS prototype (Figure 1d)

For targets with pulsed primary beams, the peak energy deposition density is given, while power densities are listed for CW beams. The CNGS target has a built-in

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redundancy in that each of 5 individual targets can be rotated into the beam for service.

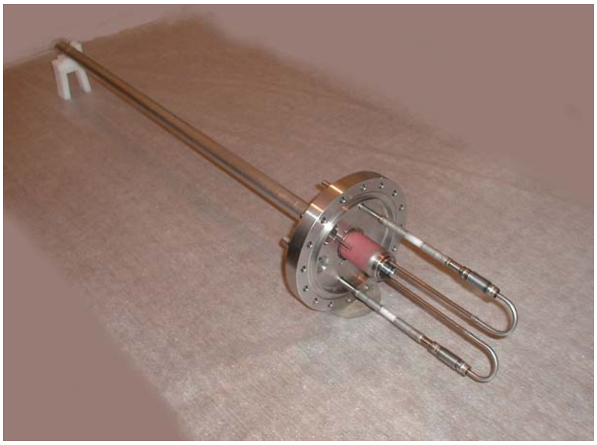

Figure 1b: The FNAL NUMI Target- segmented carbon 350 J/g pulsed water-cooled.

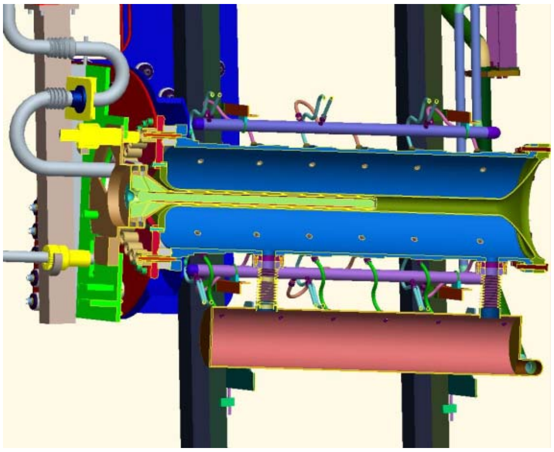

Figure 1c: The T2K Target- carbon 170 J/g pulsed He gas-cooled.

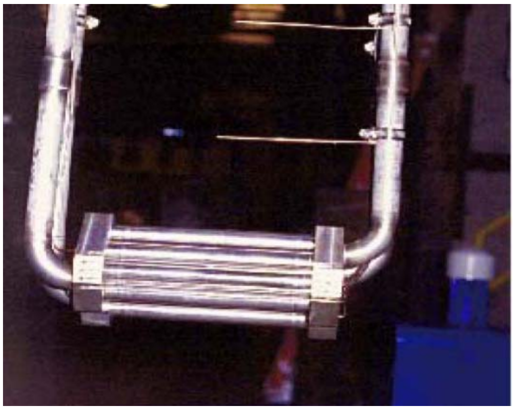

Figure 1d: The Los Alamos SNS Prototype Target- stainless steel claded tungsten 100 W/g CW water-cooled.

### *Moving Solid Targets*

Rotating target wheels are frequently used engineering solutions for efficient heat removal. Outstanding examples include:

- The T1 Kaon Production target at JPARC (see prototype in Figure 2a)
- Target-M at PSI (Figure 2b)
- The Pbar target at FNAL (Figure 2c)

The FNAL Pbar target has a redundancy in that the target disks are on a shaft that can be adjusted so that various individual disks can be independently inserted for exposure to the beam.

In each figure the approximate maximum energy deposition is given along with the nature of the primary beam and the method of cooling.

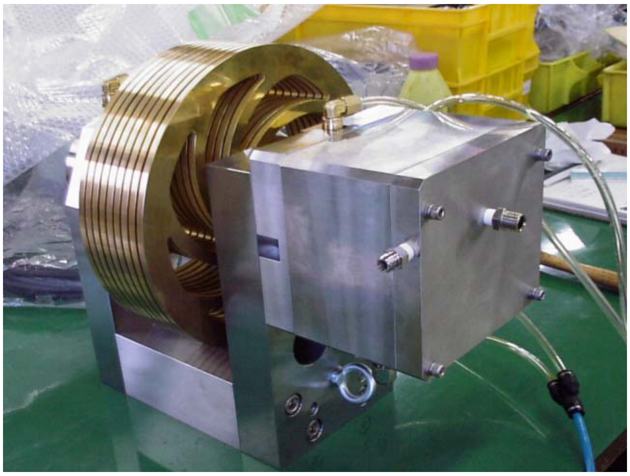

Figure 2a: The T2K Prototype Target- Ni 600J/g pulsed water-cooled.

Figure 2b: The PSI Target-M – Carbon 30W/g CW radiation-cooled.

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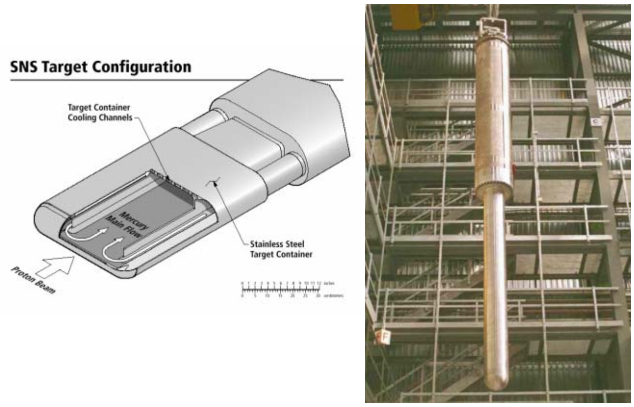
Figure 2c: The FNAL Pbar Target-Various materials 800 J/g pulsed air-cooled.

### *Liquid Targets*

Examples of liquid targets include:

- The Oak Ridge SNS target (Figure 3a)
- The PSI MEGAPIE target (Figure 3b)
- The Neutrino Factory/Muon Collider target



a) b)

Figure 3: a) The ORNL SNS Hg target and b) The PSI MEGAPIE LBE target.

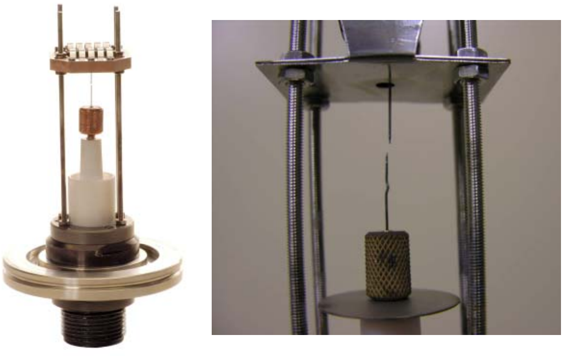
All of these examples require high-Z target material: the ORNL and PSI targets are used for the generation of neutrons for solid state studies while the Neutrino Factory requires copious pion production which is enhanced through the use of a high-Z target material. In particular, both the SNS and Neutrino Factory target use mercury (Hg) while the PSI target consists of a lead-bismuth eutectic (LBE) which is operated above 230$^0$C for operations in the liquid state. The principle advantage of these liquid targets is that the target core is easily replenished by the circulating liquid. The circulation of the liquid also leads naturally to a simple mechanism for heat removal from the core target region. The disadvantage lies in the accompanying complexity of providing for the liquid circulation.

## TARGETRY R&D

Given the array of problems facing target designers, it is natural that R&D programs would be developed in an attempt to address the formidable issues in the design of high-power targets. Some of these on-going programs are described.

### *Long Term (Fatigue) Effects*

A problem facing target development is the lack of resources suitable for the study of long-term effects. One approach being pursued at Rutherford Appleton Laboratory is to study the impact of pulsed energy deposition on candidate target material by means of electrical pulses in wires. Here both the energy deposition in the material as well as the pulse structure and rep rate can be controlled. A draw back of this approach is, of course, that the distribution of the energy deposition resulting from the flow of electric current and that by penetrating proton beams are not the same. Nonetheless, some valuable data can be obtained. We see in Figure 4a the apparatus used for these experiments and in Figure 4b an example of a resulting failure.



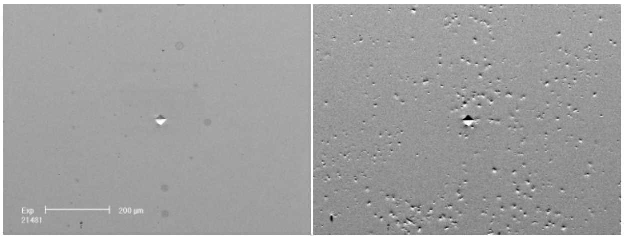
a) b)

Figure 4: a) The RAL Test Fixture and b) A resulting failure after ~$10^5$ pulses.

These tests are now ongoing but early results point to a weakness in tantalum as a high-Z target choice while tungsten is favored.

### *Hg Cavitation Effects*

At the onset of beam trials with the SNS Hg target it was noticed that pitting was occurring on the interior surface of the stainless steel jacket containing the liquid mercury (Figure 5). This effect has subsequently been identified as resulting from the forces exerted by the violent collapse of bubbles that have been generated within the mercury by the passage of the intense proton beam. An R&D program has evolved to determine how to best mitigate the resulting damage to the stainless steel jacket. Amongst the approaches considered are: a) injection of a protecting gas layer between the liquid Hg and the stainless steel, b) hardening of the stainless steel through a proprietary process know as Kolsterizing, and c) injecting He bubbles into the liquid Hg in order to absorb much of the harmful forces. An account of these activities is described in Ref. [1].



a) b)

Figure 5: The ORNL Hg Stainless Steel containment surface a) before and b) after 100 2.5 MW equivalent beam pulses.

## *The MERIT Target Experiment*

The Neutrino Factory baseline calls for a 4MW proton beam impinging on a high-Z target with narrow radial dimensions in order to mitigate re-absorption of the generated soft pions. The is done within the confines of a high-field solenoid which contains the soft pions and then conducts them down a capture channel to allow for the subsequent collection of the muon decay products (See Figure 6).

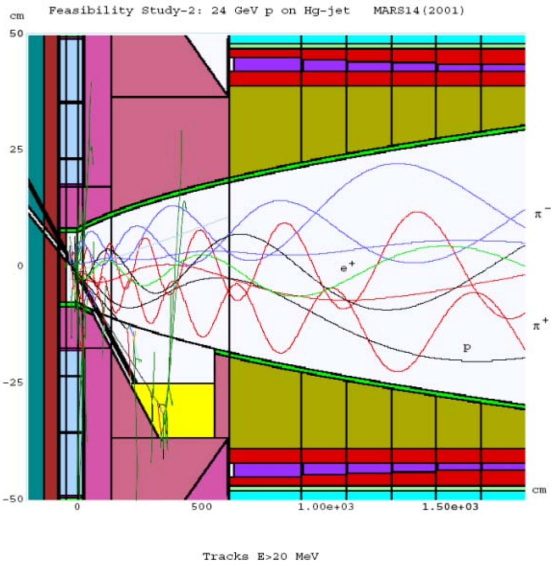


Figure 6: The Neutrino Factory Target System designed to capture as many low-energy pions of both signs as possible.

The chosen target material is liquid mercury (Hg), which presents interesting challenges in that the fluid must flow within a 15-20T-solenoid field. The velocity of the Hg jet is determined by the rep rate of the primary proton beam, hence for a 50Hz rep rate the jet must flow at ~20 m/s in order to assure that a new target is re-formed before arrival of subsequent proton pulses. Another important consideration is the nature of the cavitaion process within the Hg jet. This cavitaion and accompanying jet dispersal could influence the pion production characteristics depending on the microstructure of the primary beam.

In order to test these concepts, a proposal [2] was submitted to CERN. This proposal was approved and the experiment [3] is now in the installation phase with commissioning set to begin.

A schematic of the principal components of the experiment is shown in Figure 7. The solenoid is pulsed with a 1 second flattop at 15T. A principle goal of the experiment is to observe the MHD effects upon the Hg jet both before and after interaction with the primary proton beam. Simulations [4] show a strong MHD effect that will retard the dispersal of the Hg jet following the interaction with the proton beam.

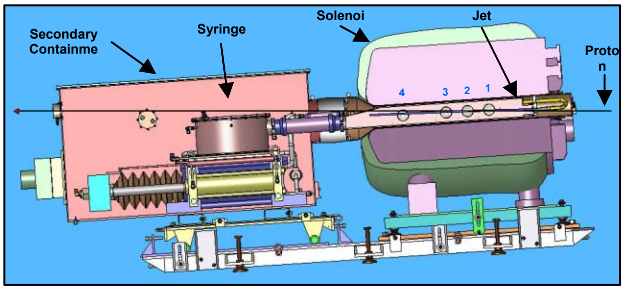


Figure 7: Schematic of the MERIT (MERcury Intense Target) experiment showing the Hg injection system and the 15T pulsed solenoid.

A discussion of the Hg delivery system can be found in Ref [5].

## *Material Properties R&D*

As pointed out earlier, the properties of the materials in and around the confines of the target have significant impact on the viability of the target system. Consequently, efforts are underway worldwide to determine the most suitable materials for various target applications.

For example, targets for pulsed beams benefit from having a low coefficient of thermal expansion, $\alpha_T$. This was clearly shown in the BNL AGS experiment E951 [6] in which two grades of graphite were exposed to identical proton beams. The carbon-carbon composite, which possesses an extremely low coefficient of thermal expansion, showed significantly reduced strain waves after the impact of the primary proton beam.

Further testing [7] of material with low coefficient of expansions (super-invar and a carbon-carbon composite) showed that this property is very sensitive to irradiation (see Figure 8)

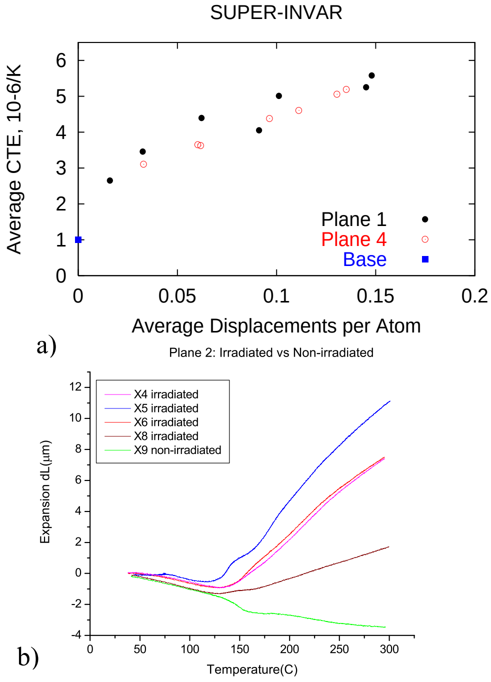


Figure 8: a) The CTE of super-invar increases by a factor of 5 with a modest 0.15 DPA (displacements per atoms) and b) The carbon-carbon composite shows similar behavior.

Subsequent testing [8] has shown, however, that the process of annealing can reverse this increase in the coefficient of thermal expansion. For super-invar, a $600^0$C heat cycle is required while for the carbon-carbon composite $200^0$C is sufficient.

Other properties of materials such as tensile strength and thermal conductivity are strongly influenced by the effects of irradiation and the testing of the impact of radiation on these and other material properties is an ongoing effort.

## CONCLUSIONS

The need for high-power targets has been well established and a worldwide program working toward there development is underway. The diversity of approaches is a hopeful sign that the issues associated with these target systems can be solved. A major impediment is the lack of suitable test beams, which would be very instrumental in speeding the development of targets. More major experiments, such as the MERIT experiment at CERN, will be required before these target systems can be fully developed and implemented.

## ACKNOWLEDGMENTS

This work was supported by the U.S. DOE under contract No. DE-AC02-98CH10886.

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